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THE PASSIVE CHARACTERISTICS OF A REPULSION MAGNETIC BEARING

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SUMMARY

Magnetic suspension systems can meet the requirements for spacecraft momentum wheel bearings. The main aim of the work described in this Report was to investigate the effects of interleaving soft iron spacer rings of various thicknesses between the magnetic rings of a repulsion type magnetic bearing. An optimum thickness of iron ring was found which produced a maximum increase in radial stiffness over the stiffness obtained without iron spacers. The magnetic inhomogeneity of the magnets was measured and found to have a small effect on the radial stiffness. Theory predicts that a single repulsion bearing will be cross-axially stable if the ratio of its length to diameter exceeds $\sqrt{3}$. This value was confirmed within the uncertainty of the experiment. The external magnetic fields from representative bearing assemblies were measured.

Departmental Reference: Space 516

CONTENTS

1 INTRODUCTION

Since the earliest days of space exploration, attitude control has often been achieved through the gyroscopic properties of a rotating mass. The most common technique has involved rotation of the complete spacecraft. In recent years, there has been an increasing requirement for parts of spacecraft to remain fixed relative to some defined direction. An example is the need for communications aerials to remain pointing at the Earth. This has led to mechanically despun components of a body otherwise rotationally stabilised. It is a logical development of such a system to remove the angular momentum storage from the main spacecraft body to a high speed, low mass wheel. The design of such a wheel poses several problems, particularly as the most likely applications require lifetimes of the order of ten years. Conventional ball and grease bearings both involve contact between the parts in relative motion; hence wear takes place. Furthermore there are difficulties in maintaining a lubricating film in a vacuum and while weightless. Such problems, and the related problems of gas bearings, may not be insoluble, but their nature is such that bearings designed by these principles cannot be shown to have the lifetimes needed without ground testing lasting at least as long as those proposed lives.

An ideal suspension system for a spacecraft momentum wheel needs to be non-contacting, have a predictable likelihood of failure and have the potential for reducing the risk of failure by including redundancy into the design. These requirements, and others normal to spacecraft such as immunity from radiation, thermal acceptability to and compatibility with existing spacecraft systems, can be met by a magnetic suspension system.

Magnetic suspension systems can take many forms and use several different principles. The magnetic forces used may be produced by electromagnets or permanent magnets or both. The suspension may be achieved through the attraction of unlike poles, or the repulsion of like poles. Devices using diamagnetic or superconducting materials are as yet impractical in this application. All other devices are constrained by Earnshaw's Theorem[1], which in this context denies the existence of a stable equilibrium position for a wheel supported by a time invariant magnetic field. In other words, at least one degree of translational freedom needs to be actively servo controlled electromagnetically. With one rotational degree of freedom controlled by a motor this leaves the remaining four degrees of freedom to be passively controlled by permanent magnets.

This Report does not seek to compare or evaluate relative merits or drawbacks between alternative systems. As yet there is no design which even in principle offers a clear advantage over its rivals. Mainly passive systems, that is those with maximum control by permanent magnets, can use the attraction or repulsion principle. Theoretically neither type has any advantage over the other, although in the future there may be practical reasons for a preference. Mainly or wholly active systems, which are those using servo control in more than one axis, have advantages and disadvantages which can only be evaluated in the light of a specific application. But in all cases, mechanical contact and therefore wear is removed and the reliability of the suspension is very nearly the reliability of the control electronics, which can be confidently predicted. Furthermore, duplication of electronics can provide redundancy, hence increasing the reliability of the system.

Mainly passive magnetic suspensions, in particular those using the repulsion principle, have only become feasible with the advent of commercially available samarium cobalt magnets. Samarium cobalt[2], $SmCo_5$, is one of a family of rare earth permanent magnet compounds and offers previously unavailable performance. Its advantages over existing permanent magnets are: a very high energy product of about $120 kJ/m^3$; a very high intrinsic coercivity of 1200kA/m and an intrinsic demagnetizing curve which is almost rectangular; a recoil permeability of nearly unity, even when the flux density is reversed by a demagnetizing field. These properties permit magnets to be operated over a wide dynamic range about the maximum energy product point and to be used in repulsion configurations which would demagnetise other materials.

A mainly passive suspension system consists of two major parts. First, there are the permanent magnetic bearing elements. Secondly, there is the axial position controller, consisting of force coil, sensors and servo control loop. This Report describes an investigation into the passive, permanent magnet aspects of a particular design of repulsion bearing. Briefly, such a bearing, shown diagrammatically in Fig.1, consists of an outer shell of permanent magnet rings, magnetized axially, with the rings stacked with like poles adjacent and a coaxial inner shell of magnet rings of the same thickness and stacked in exact correspondence with the outers. This is not a new design[3], but until the advent of samarium cobalt as previously described, it could only be realised by using anisotropic ferrite magnets which have a maximum energy product of about $25 kJ/m^3$. Samarium cobalt magnets produce about five times more force than ferrites from a given volume of material. It is easy to see that a radial displacement of the inner relative to the outer leads to a positive restoring force to the centre, but an axial displacement produces a negative, destabilizing force tending to increase the displacement. In other words, the two radial degrees of freedom are passively controlled, but the axial direction requires active control. Rotation about the bearing axis is accomplished without any losses as the bearing is radially symmetrical. It is less immediately obvious but was predicted from dynamic analysis[4] by Plimmer that the two rotational degrees of freedom about the radial axes are passively controlled if the bearing has a length to diameter ratio greater than a certain critical value.

The major aim of this work has been to experiment with soft iron spacers in between the magnet rings described above to discover if thereby the performance of bearings designed to this principle can be improved and to arrive at design criteria which point to an optimized bearing. How, and why, this was achieved is described later. A simultaneous effort was made, but with lower priority, to confirm the limiting ratio of length to diameter needed for cross-axis stability. Finally, the external field from a representative bearing assembly has been assessed. Some related work has been carried out within the RAE on force coil and amplifier systems[5], that is the second part of a magnetic suspension system as described above.

2 BEARING STIFFNESS MEASUREMENTS

2.1 Required measurements

The stiffness [illegible] an actively controlled axis can be adjusted freely within the constraints of [illegible] available within the control loop. However, for a given design, only [illegible] limited adjustment of the stiffnesses of passively controlled axes is [illegible]. Therefore it is essential that passive axis stiffnesses can be accurately predicted. Backers' theory[3], based on an approximate two-dimensional analysis predicts that:

$$S_R = \frac{0.655 \ell r M^2}{2\mu_0 C} \qquad (1)$$

where S_R = radial stiffness

ℓ = bearing length

r = bearing mean radius

M = intensity of magnetization

μ_0 = primary magnetic constant

C = clearance between inner and outer

provided that

$$c > \frac{a}{2} \tag{2}$$

where a = the ring thickness.

This analysis also assumes that

$$\frac{dM}{dH} = 0$$

where H = magnetizing force.

This relation is very nearly true for samarium cobalt for H less than the intrinsic coercivity since as mentioned before, this material has an almost rectangular intrinsic demagnetizing curve. But samarium cobalt is fairly expensive, difficult to machine and fragile. The intention for these tests was to use a samarium cobalt powder impregnated resin with the commercial name HERA. This material, it was believed, offered the same properties as samarium cobalt, albeit with a maximum energy product of $55kJ/m^3$ and a slightly reduced coercivity. Nevertheless, the essential principle of the intensity of magnetization being invariant with magnetizing force was expected to remain. The great advantages of HERA were that it was cheap, costing only a few pence per gramme, very easy to machine, readily available and relatively robust. The first task was to measure the stiffness of a HERA bearing to confirm that its magnetic properties conformed with the theory. Once this was done, the real work was begun.

The main points of the work programme were as follows:

First, to measure the relationship between the positive radial stiffness and the negative axial stiffness. As a consequence of Earnshaw's Theorem it was expected that for this type of radially passive bearing, using material whose intensity of magnetization would remain constant over all operating conditions, the axial stiffness S_A should be equal to $-2S_R$. Confirmation of this relationship would then support the assumption that the intensity of magnetization was invariant.

Secondly, to measure the variation of axial and radial stiffness when the inner and outer magnets were relatively displaced radially and axially. The theoretical predictions for stiffness assume that the bearing is in the symmetrical state shown in Fig.1. In operational practice the inner and outer magnets will at times be relatively offset as loads are applied to the bearing. It was necessary to measure how the stiffness characteristics were degraded by offsets so that allowable excursions could be established for practical bearings.

Thirdly, to measure the axial and radial stiffnesses with soft iron spacers incorporated between the magnet rings. As the saturation magnetization of iron was higher than the intensity of magnetization of the magnets it was expected that increased radial stiffness could be obtained. However, in the iron it was not clear how the magnetization would be affected by relative movement between the inner and outer bearing magnets. Therefore a series of measurements was proposed using different spacer thicknesses in an attempt to establish a trend.

Fourthly, to measure the inhomogeneity of the magnetization of the magnet rings and relate this if possible to any change in radial stiffness as the inner magnets were rotated about the bearing axis. If the magnet rings were not uniformly magnetized there may be a tendency for the bearing to have a preferred alignment which during rotation could produce unwanted oscillations or coning. Further, it was proposed to attempt to assess the influence of the soft iron spacers on these effects.

2.2 Test rig and bearings

The bearing test rig was designed to accommodate six pairs of magnet rings, inners and outers, in a repulsion bearing configuration. Spacers of up to the individual ring thickness could be interleaved between the magnets. The outer magnets were held in a housing constrained by screw jacks such that they could be moved relative to the inners axially and radially. The screw jacks were calibrated so that the displacement could be measured. The inner magnets were held on a shaft. The shaft was free to slide and swivel at one end in a universal joint. The other end was fixed to a rigidly mounted force transducer measuring the axial force on the shaft. A second force transducer mounted at right angles to the shaft measured the radial force on it. Simultaneous measurement of the axial and radial forces was possible because the transducers used allowed less than 0.04mm movement along their line of action while allowing free movement, over a limited range but one much greater than 0.04mm, in a plane normal to their line of action.

Three different bearing sizes were used, two using HERA rings and one using samarium cobalt rings. The sizes are shown in Table 1. The test rig incorporated sleeves and bushes on the inner shaft and outer housing to accept the different sizes. All the tests using HERA magnets used six pairs of rings. The first test using samarium cobalt magnets without spacers used five outers and three inners. Subsequently an outer magnet was broken so for all the rest of these tests four outers and three inners were used.

..3 Variation of stiffnesses with displacement

(a) Axial stiffness variation with radial offset

This test was carried out using the 4mm thick HERA rings included in Table 1 without any spacers. The variation of the axial force on the inner shaft was measured as the outer magnets and housing were displaced axially either side of the central position. The measurement was repeated with the outer magnets displaced radially by [illegible]mm and 0.9mm with respect to the inners. The results are shown in Fig.2. The destabilizing axial stiffness increased from 5[illegible].4N/mm with no radial displacement to [illegible]N/mm with 0.5mm radial offset and to 58.9N/mm at 0.9mm radial offset. This is consistent with the increase in stiffness being proportional to the square of the offset. Fig.3 shows the variation of radial force with axial displacement for different radial offsets. The asymmetry of the curves shown in Fig.3 is interpreted as being due to the cross-axis instability of such a short bearing.

(b) Radial stiffness variation with axial offset

Two tests were carried out. The first, using 4mm thick HERA rings was to measure the variation in the radial force on the shaft with radial displacement for relative axial offsets between inner and outer magnets of 0, 0.21mm and 0.42mm. The results are shown in Fig.4. The positive radial stiffness reduced from 25.1N/mm with no axial displacement to 23.4N/mm with 0.21mm axial offset and to 21.1N/mm with 0.42mm axial offset. This suggests that for small offsets the change in radial stiffness is linear with axial offset. Fig.5 shows the variation of axial force with radial displacement for different axial offsets As with the corresponding radial force measurement, the effect of the cross-axis instability is apparent in the displacement of the axial force minimum from the zero position.

The second test used 1.5mm thick HERA rings to ascertain whether the effect of axial displacement on the radial stiffness was affected by the inclusion of soft iron spacers. The results are shown in Fig.6. Without spacers, the measured radial stiffnesses were 17.3N/mm with no axial offset and 13.5N/mm with an axial offset of 0.21mm. For the same axial offsets the radial stiffnesses were 21.1N/mm and 15.6N/mm when 0.076mm thick soft iron spacers were interposed between adjacent magnet rings. The selection of this particular spacer thickness will be justified later. The stiffness was reduced by the same proportion in both cases.

2.4 Variation of stiffnesses with spacer thickness

This test was carried out using all three different magnet ring sizes. Each part of the test was to measure the axial force variation with axial displacement about the zero position and the radial force variation likewise with radial displacement with soft iron spacers of a particular thickness interposed between the magnet rings. The spacer thicknesses used and the results obtained with each type of magnet ring are given on Figs.7 to 16. The distinction between the thick and thin spacers referred to in the titles to those figures is relative and designed to avoid the attempted presentation of too much information on one figure. In fact 'thick' spacers had a thickness equal to or greater than one tenth of the thickness of the magnet rings with which they were used. 'Thin' spacers were those less than one tenth of the magnet thickness. In general the spacers were the same diameters as the magnets with which they were used. The exceptions were the thin spacers used with the 4mm thick HERA magnets, which for convenience had the same diameters as the 1.5mm thick HERA magnets.

The results are summarized for the 4mm thick HERA, 1.5mm thick HERA and samarium cobalt rings in Tables 2, 3 and 4 respectively. The most interesting feature is that the radial stiffness with spacers about 0.1mm thick was greater than that with no spacers. Fig.17 shows how the radial stiffness varied with spacer thickness for each of the three ring types. The optimum spacer thickness for maximum radial stiffness was slightly greater using samarium cobalt magnets than using HERA ones. The ratio of axial to radial stiffness was very close to 2:1 for spacer thicknesses less than the optimum. These observations indicated that the increase in stiffness was due to the flux density in the iron exceeding that in the magnets. The optimum thickness occurred when all the iron was just saturated all the time. Then the criterion that $dM/dH = 0$ in the magnetic material was satisfied again and the stiffness ratio tended to 2:1. Reducing the thickness further reduced the volume of magnetic material without increasing the flux density as the iron was saturated and so the radial stiffness decreased linearly with spacer thickness to the no spacer value, while the 2:1 ratio was maintained. The optimum thickness using samarium cobalt magnets was greater because the intrinsic magnetization of that material, 0.75T was greater than that of HERA, 0.55T. There was no measurable difference between the optimum thickness using 4mm and 1.5mm, as would be expected from the above qualitative analysis since the intrinsic magnetization is a function of the material, not its dimensions. Using equation (1) the stiffnesses of bearings made up from a permanent magnet part and a saturated iron part with a saturation flux density in the iron of 1.8T have been calculated and are compared with the measured values in Tables 5, 6 and 7. They show that good correlation was obtained.

Figs.8 and 12 show that near the maximum possible radial displacements, the radial stiffness was not constant when thick iron rings were incorporated between the magnets. A qualitative explanation for this effect is that because of the highly demagnetizing fields existing under those conditions the magnetic flux was short circuited by the unsaturated iron. There was no evidence for a similar effect using the thin iron spacers, which suggests further confirmation that in those circumstances, they were always saturated.

2.5 Variation of stiffnesses with iron sleeving

Figs.18 and 19 show the results after fitting an iron sleeve 5mm thick over the outer 4mm thick HERA magnets. The purpose was to assess the usefulness of such a sleeve in reducing the external magnet field from the bearing and to find out to what extent the bearing performance would be degraded.

The axial stiffness was -46N/mm and the radial stiffness was 23N/mm. It will be seen later that the reduction in stiffnesses is almost exactly the same as the reduction in external magnetic field. This suggests that sleeving of this type is not suitable as a way of reducing the external field.

2.6 Effects of magnetic inhomogeneity

The axial flux density of each ring was measured using a Hall effect magnetometer as near as possible to the inner edge of the outer magnets and the outer edge of the inner magnets. The active element of the Hall probe was about 5mm long by 1mm wide and measured the flux density normal to its face. The measurements were made with the long axis of the probe element aligned radially.

All the HERA rings displayed the same characteristic pattern of flux density with a single maximum and a single minimum diametrically opposite, with a smooth transition between them. For two of the four cracked rings, the minimum was coincident with a crack in the ring. Table 8 shows the maximum and minimum flux density measured for each of the HERA rings with the percentage variation in each case. Several attempts were made to measure the variation of radial stiffness with the relative angular position of the inners with respect to the outers, by measuring the stiffness, rotating the inners through 90° then remeasuring. Both 4mm and 1.5mm thick rings were used, without spacers. There was no detectable variation in radial stiffness.

Table 9 shows the results using the samarium cobalt rings. The flux density from these was measured for each ring without spacers and then with first a 0.25mm iron ring on each face, then with 2.5mm iron rings. With a single exception, all the rings showed the same diametrically opposed maximum and minimum as the HERA rings. One of the outer rings however, had two maxima diametrically opposite and two minima on a diameter displaced 90° from the maxima. Another of the outer rings was broken after measuring without spacers and was not subsequently used. One of the inners was broken into four pieces and could only be used when held between two 0.25mm spacers. The results show that the variation in flux density was in some cases very high and that iron facing pieces in the worst cases approximately halved the difference between maximum and minimum. Fig.15 shows the difference between the radial stiffnesses obtained before and after the inner magnets were displaced through 90°. In one position the radial stiffness was 28.8N/mm; in the other it was 28.2N/mm. The 0.25mm iron spacers were incorporated between the rings. The problems involved in assembling the broken inner ring into the test rig were too great to permit a comparison without spacers.

3 CROSS-AXIS STABILITY

Analysis has shown[4] that a bearing of the type examined in this work should have positive angular stiffness if the ratio of the bearing length, ℓ, to the diameter of the inner magnets, d, exceeds $\sqrt{3}$. This prediction can be confirmed using a simple pendulum as shown in Fig.20. The inner magnets become the pendulum bob, constrained axially by the rigid pendulum arm. The outer magnets are rigidly mounted.

Practical bearings would be designed to operate well away from the critical region. However, confirmation of such a prediction improves confidence in the analysis from whence it came.

For such a pendulum where the mass of the inner magnets is M' kg, the mass of the arm is M kg, the dimensions are as shown in Fig.20 and the bearing radial stiffness is S_R N/m the oscillation frequency ω rad/s can be shown to be given by:

$$\omega^2 = \frac{S_R(L'^2 - d^2/4 + \ell^2/12) \pm M'gL' \pm Mg\ell}{M'(\ell^2/4 + L'^2) + ML^2/3} .$$

The signs of the second and third terms of the numerator depend on whether the pivot of the pendulum is above or below M'. However, it is the first term in the numerator which is the significant one in establishing the critical length to diameter ratio. This term can be rewritten

$$S_R\left[L'^2 + \frac{1}{4}\left(\frac{\ell^2}{3} - d^2\right)\right] .$$

The term $\frac{\ell^2}{3} - d^2$ appears as a direct consequence of the assumption that positive angular stiffness results when $\ell > \sqrt{3}d$. If the constant of proportionality were not $\sqrt{3}$, or the criterion for angular stability were not the simple relationship, ℓ and d would appear in the above with different constants or in different ways. Therefore in principle an accurate determination of the period of such a pendulum would be sufficient to confirm the relation in question.

In practice, $\frac{\ell^2}{12} - \frac{d^2}{4}$ must be significantly large with respect to L'^2 with the other parameters also accurately known before a sufficiently sensitive measurement can be made.

Barium ferrite ring magnets were used to construct pendulums. The number of inners used were 1, 2, 3, 4 and 8. In each case, first the frequency of a long pendulum was measured; with L' long, the ℓ and d terms became negligible and S_R could be accurately calculated. Using these values of S_R, the curves shown in Fig.21 were drawn predicting the behaviour of short pendulums such that the ℓ and d terms became significant. Then short pendulums were made, using the same magnet rings as had been used in each case for the long pendulums. Their oscillation frequencies were measured and are plotted on Fig.21. The estimated total uncertainty due to measurement accuracy is ±9%. However, there was another potential source of error, namely that the radial stiffness reduces with axial movement away from the central position. Using long pendulums this effect was negligible as the angular motion was very small. However with short pendulums the allowable angular deflection was much greater and significant axial movement could occur. Special attention therefore had to be paid to ensuring that the oscillation frequency was measured with the smallest possible deflection. In general this was not a problem, except in the case of the one-ring pendulum. Then the low inertia led to rapid damping of the pendulum motion and consequently to difficulty in measuring the period when the deflection was suitably small. Therefore it is not surprising that the discrepancy between observed and predicted frequency in this case is the only one outside the tolerance quoted above.

4 EXTERNAL MAGNETIC FIELD

The peak magnetic flux density was measured at a distance of 66m from the axis of the bearing. The field direction was parallel to the axis. The position of the maximum flux density was in line with the end of the bearing.

Using 4mm thick HERA rings the external flux density was measured for three configurations. With no spacers the external field was 0.165mT. With 0.076mm thick spacers it was 0.178mT. Finally, without spacers and with an iron sleeve over the outers, the measured field was 0.143mT. A single measurement was made using samarium cobalt rings with 0.051mm thick spacers and the external field was 0.275mT.

5 CONCLUSIONS

The restricted time available to complete this work programme has left some results open ended or inconclusive. The major aim, to investigate the effects of soft iron spacers between the magnet rings, has been satisfactorily met. The radial stiffness of a bearing can thereby be increased usefully without disproportionately increasing the axial destabilizing stiffness and with a smaller penalty in mass and dimensions than would result from adding more magnets. Additionally the iron spacers reduce the variation in flux density outside the rings which should reduce the variation in stiffness as the bearing rotates.

The limited data from the cross-axis stability experiment support the claim for a critical length to diameter ratio of $\sqrt{3}$. A more through investigation is needed to be conclusive. The technique used is believed to be sound, but better apparatus using HERA magnets would reduce the uncertainty.

Only a cursory attempt to measure the external field was possible. As was expected this showed that a magnetic suspension using this principle would be embarrassing on a magnetically sensitive spacecraft. However at synchronous height where most applications lie few spacecraft are magnetically sensitive. It is conceivable that an attraction system using a closed magnetic circuit may be preferable, but leakage would probably be so great that there would be little to choose between it and a repulsion system. More information is needed on the feasibility of magnetic shielding.

Table 1

DIMENSIONS OF MAGNET RINGS USED FOR BEARING STIFFNESS MEASUREMENTS

Material	Outer magnets: Outside diameter mm	Outer magnets: Inside diameter mm	Inner magnets: Outside diameter mm	Inner magnets: Inside diameter mm	Thickness mm
$SmCo_5$	56.2	46.2	44.6	34.5	2.54
HERA	45.0	37.4	34.8	24.2	4.0
HERA	45.0	37.0	35.4	24.2	1.5

Table 2

AXIAL AND RADIAL STIFFNESSES USING 4mm THICK HERA RINGS AND SOFT IRON SPACERS

Spacer thickness mm	Axial stiffness S_A N/mm	Radial stiffness S_R N/mm	Ratio $-S_A/S_R$
2.0	-72.3	8.3	8.7
0.8	-75.9	15.9	4.8
0.4	-75.7	18.8	4.0
0.15	-68.1	27.0	2.5
0.076	-60.1	29.4	2.0
0.051	-57.4	28.0	2.0
0	-52.6	25.1	2.1

Table 3

AXIAL AND RADIAL STIFFNESSES USING 1.5mm THICK HERA RINGS AND SOFT IRON SPACERS

Spacer thickness mm	Axial stiffness S_A N/mm	Radial stiffness S_R N/mm	Ratio $-S_A/S_R$
1.5	-66.0	7.7	8.6
0.75	-80.3	13.2	6.1
0.3	-75.9	18.4	4.1
0.15	-60.0	21.2	2.8
0.076	-46.6	21.8	2.1
0.051	-40.9	21.4	1.9
0.025	-35.0	19.8	1.8
0	-33.3	18.4	1.8

Table 4

AXIAL AND RADIAL STIFFNESSES USING SAMARIUM COBALT RINGS AND SOFT IRON SPACERS

Spacer thickness mm	Axial stiffness S_A N/mm	Radial stiffness S_R N/mm	Ratio $-S_A/S_R$
0.25	112.6	28.8	3.9
0.102	102.3	44.6	2.3
0.051	94.6	38.6	2.4
0	76.7	36.6	2.1

Table 5

COMPARISON BETWEEN PREDICTED AND MEASURED VALUES OF RADIAL STIFFNESS USING 4mm HERA RINGS AND THIN IRON SPACERS

Spacer thickness mm	Predicted radial stiffness N/mm	Measured radial stiffness N/mm
0.076	33.5	29.4
0.051	31.1	28.0
0	26.3	25.1

Table 6

COMPARISON BETWEEN PREDICTED AND MEASURED VALUES OF RADIAL STIFFNESS USING 1.5mm HERA RINGS AND THIN IRON SPACERS

Spacer thickness mm	Predicted radial stiffness N/mm	Measured radial stiffness N/mm
0.076	23.3	21.8
0.051	20.9	21.4
0.025	18.5	19.8
0	16.1	18.4

Table 7

COMPARISON BETWEEN PREDICTED AND MEASURED VALUES OF RADIAL STIFFNESS USING SAMARIUM COBALT RINGS AND THIN IRON SPACERS

Spacer thickness mm	Predicted radial stiffness N/mm	Measured radial stiffness N/mm
0.102	36.6	44.6
0.051	34.1	38.6
0	31.7	36.6

Table 8

VARIATION OF MEASURED FLUX DENSITY FROM HERA MAGNET RINGS

Maximum flux density mT	Minimum flux density mT	Variation %	Remarks
4mm thick HERA outer			
37.0	35.6	3.9	
33.8	30.2	11.9	Cracked, no correlation
35.0	32.2	8.7	Edge flaked, no correlation
38.2	35.0	9.1	
34.0	32.2	5.6	
37.8	34.6	9.2	Cracked, no correlation
4mm thick HERA inner			
46.0	44.0	4.5	
43.5	42.6	2.1	
43.9	43.0	2.1	
44.8	42.5	5.4	
44.0	42.8	2.8	
45.2	43.9	3.0	
1.5mm thick HERA outer			
16.4	15.8	3.8	
16.1	15.6	3.2	
17.2	15.8	8.9	Minimum coincident with crack
17.1	16.3	4.9	
16.7	16.0	4.4	Minimum coincident with crack
17.4	16.4	6.1	
1.5mm thick HERA inner			
25.0	24.2	3.3	
25.0	23.5	6.4	
24.0	23.0	4.3	
25.0	24.0	4.2	
26.0	25.0	4.0	
27.0	25.0	8.0	

Table 9

VARIATION OF MEASURED FLUX DENSITY FROM SAMARIUM COBALT RINGS

Maximum flux density mT	Minimum flux density mT	Variation %	Remarks
No iron rings - outer			
46.5	45.0	3.3	
44.5	43.0	3.5	
45.5	36.7	24.0	Two maxima and minima
46.5	43.5	6.9	
44.0	43.2	1.9	Minimum conicident with crack
No iron rings - inner			
49.0	42.5	15.3	
49.0	48.0	2.1	
0.25mm facing rings - outer			
50.0	48.0	4.2	
47.5	46.5	2.2	
48.0	42.5	12.9	Two maxima and minima
50.0	47.5	5.3	
0.25mm facing rings - inner			
61.0	56.0	8.9	
65.0	62.0	4.8	
65.0	39.0	66.7	In four pieces
2.5mm facing rings - outer			
63.0	59.0	6.8	
59.0	56.0	5.4	
63.5	58.0	9.5	Two maxima and minima
56.5	55.0	2.7	
59.5	57.0	4.4	
2.5mm facing rings - inner			
68.5	66.0	3.8	
72.0	70.5	2.1	

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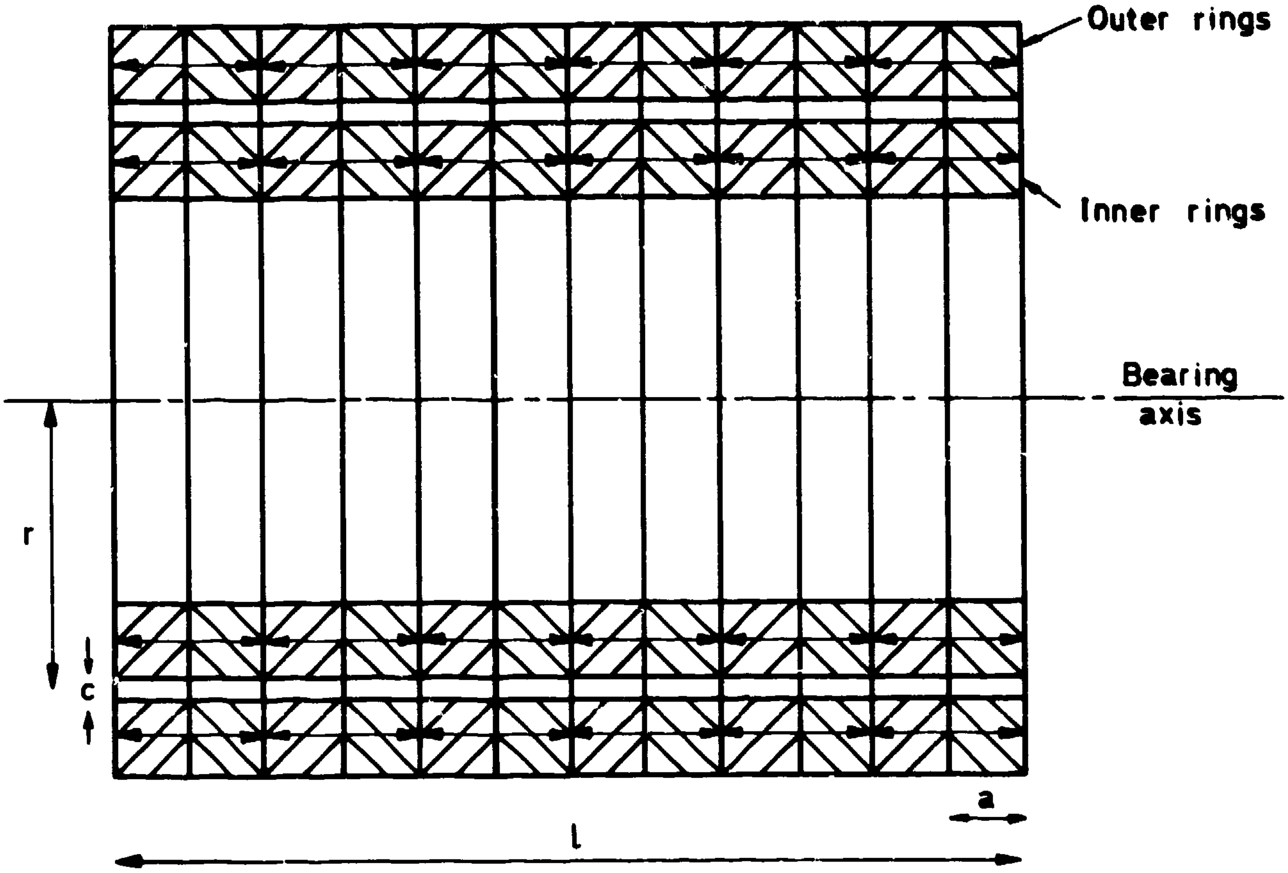

Arrows show direction of magnetization in each ring

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Fig.1 Cross section through repulsion type magnetic bearing

Fig. 2

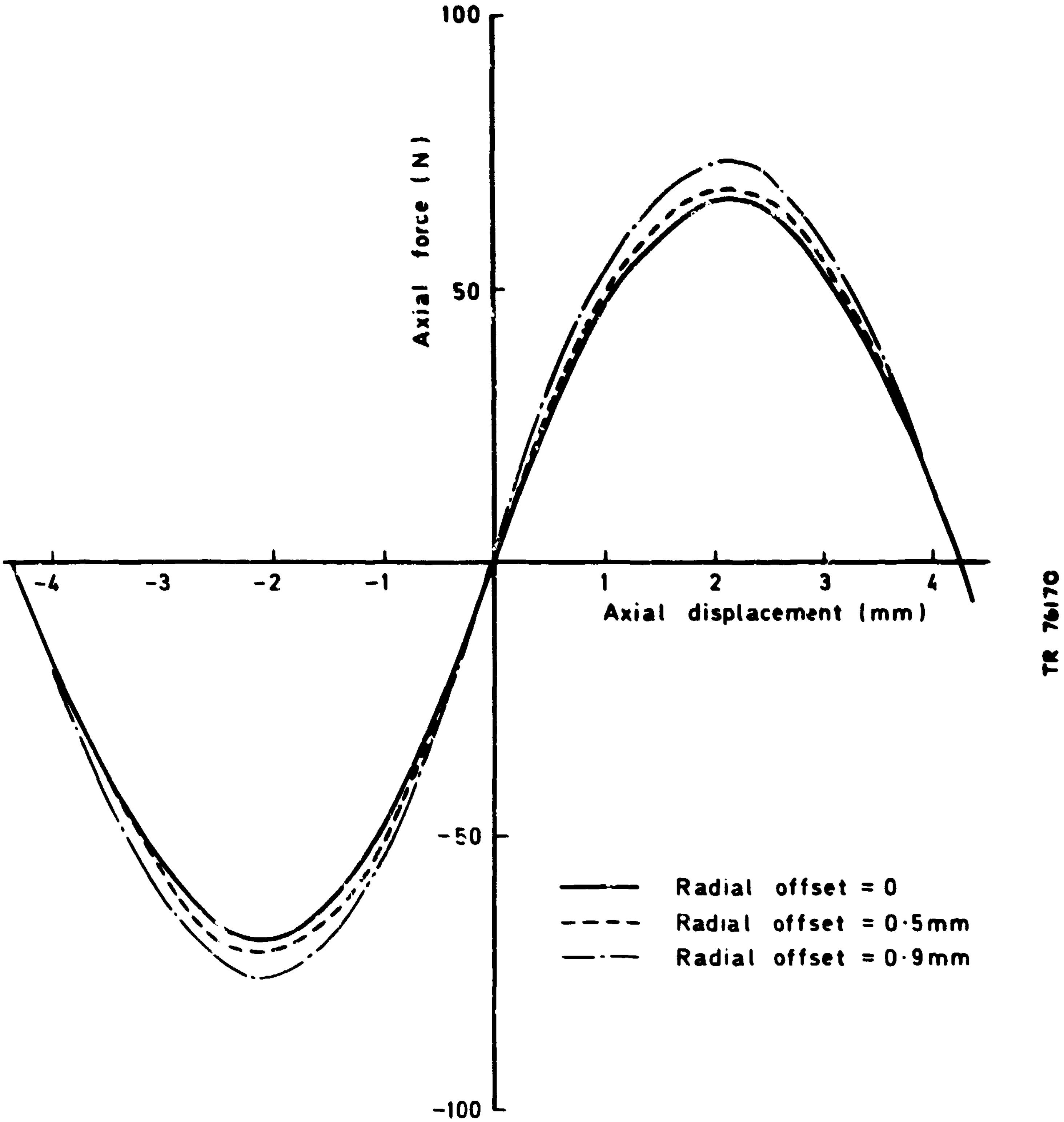

Fig. 2 Variation of axial force with displacement using 4mm HERA rings with no spacers for different radial offsets

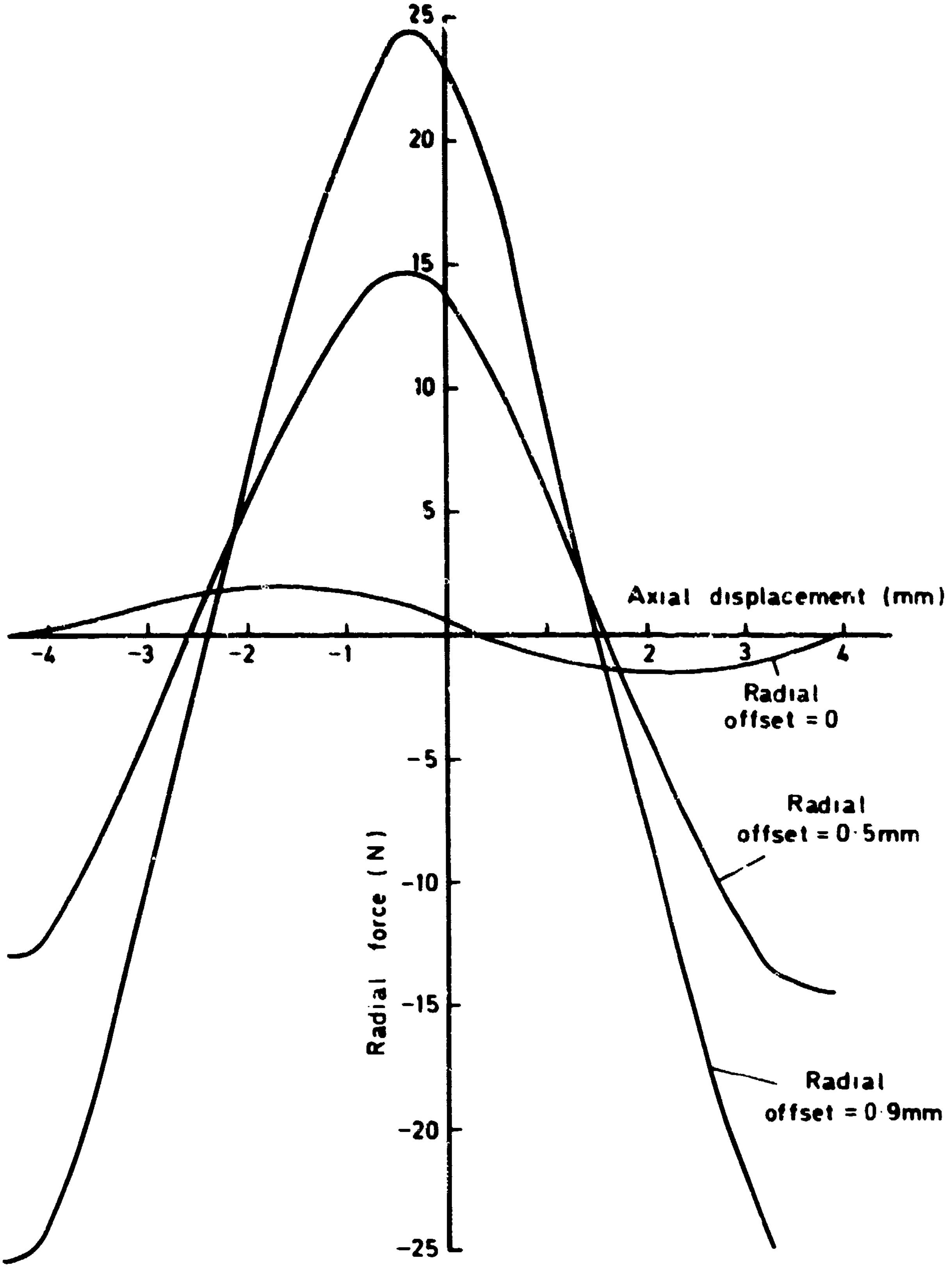

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Fig. 3 Variation of radial force with axial displacement using 4mm HERA rings with no spacers for different radial offsets

Fig. 4

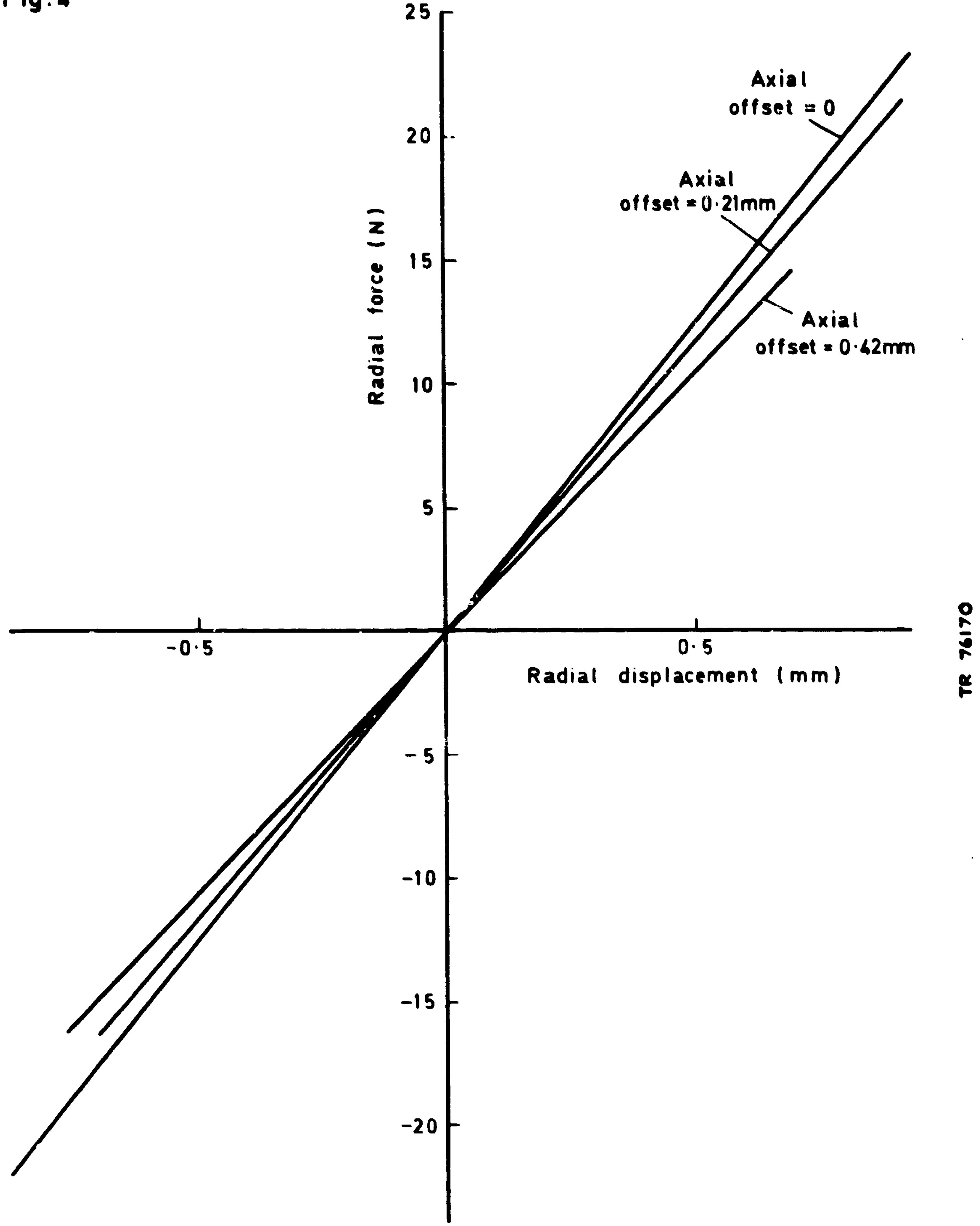

Fig. 4 Variation of radial force with displacement using 4mm HERA rings with no spacers for different axial offsets

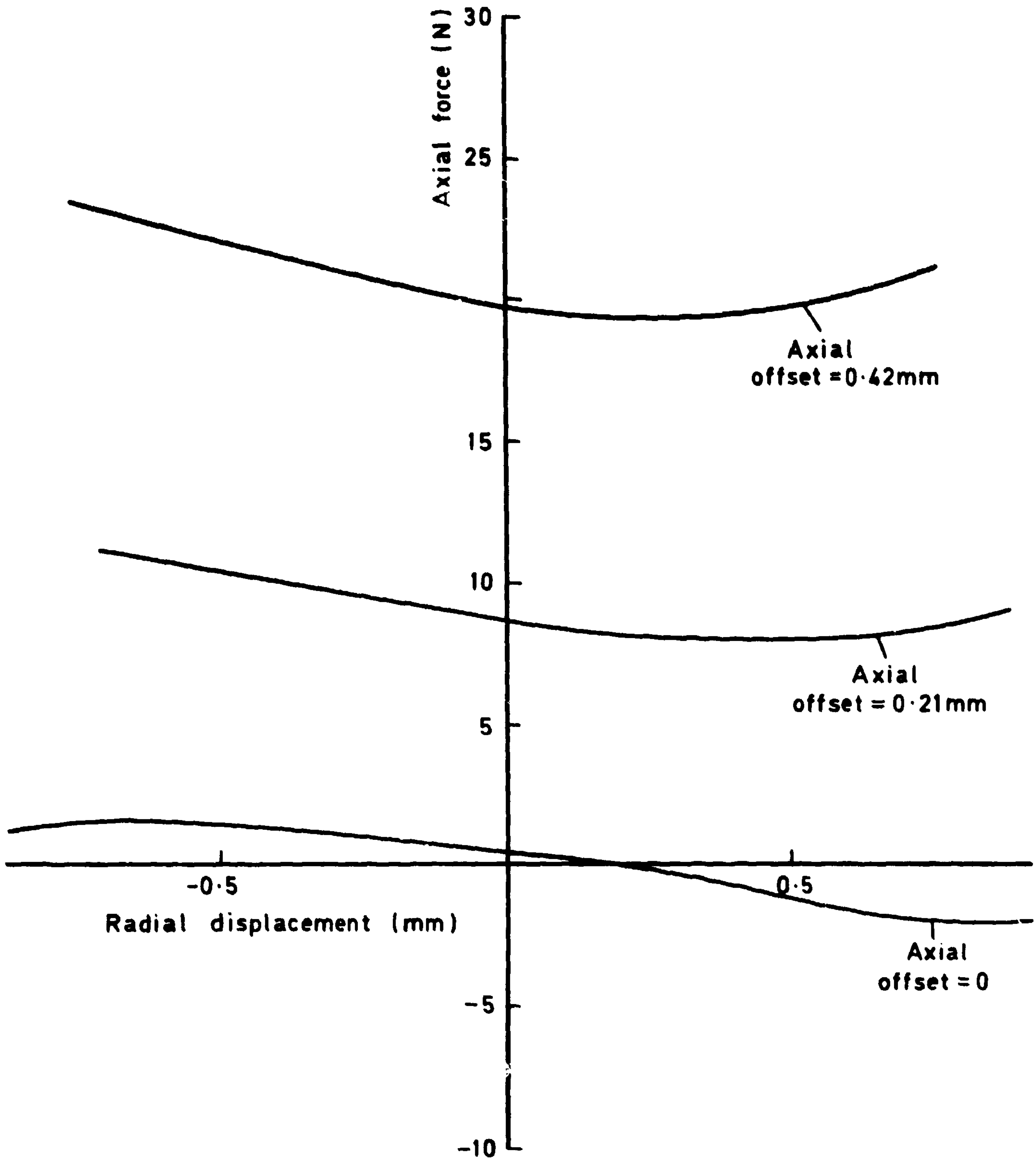

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Fig. 5 Variation of axial force with radial displacement using 4mm HERA rings with no spacers for different axial offsets

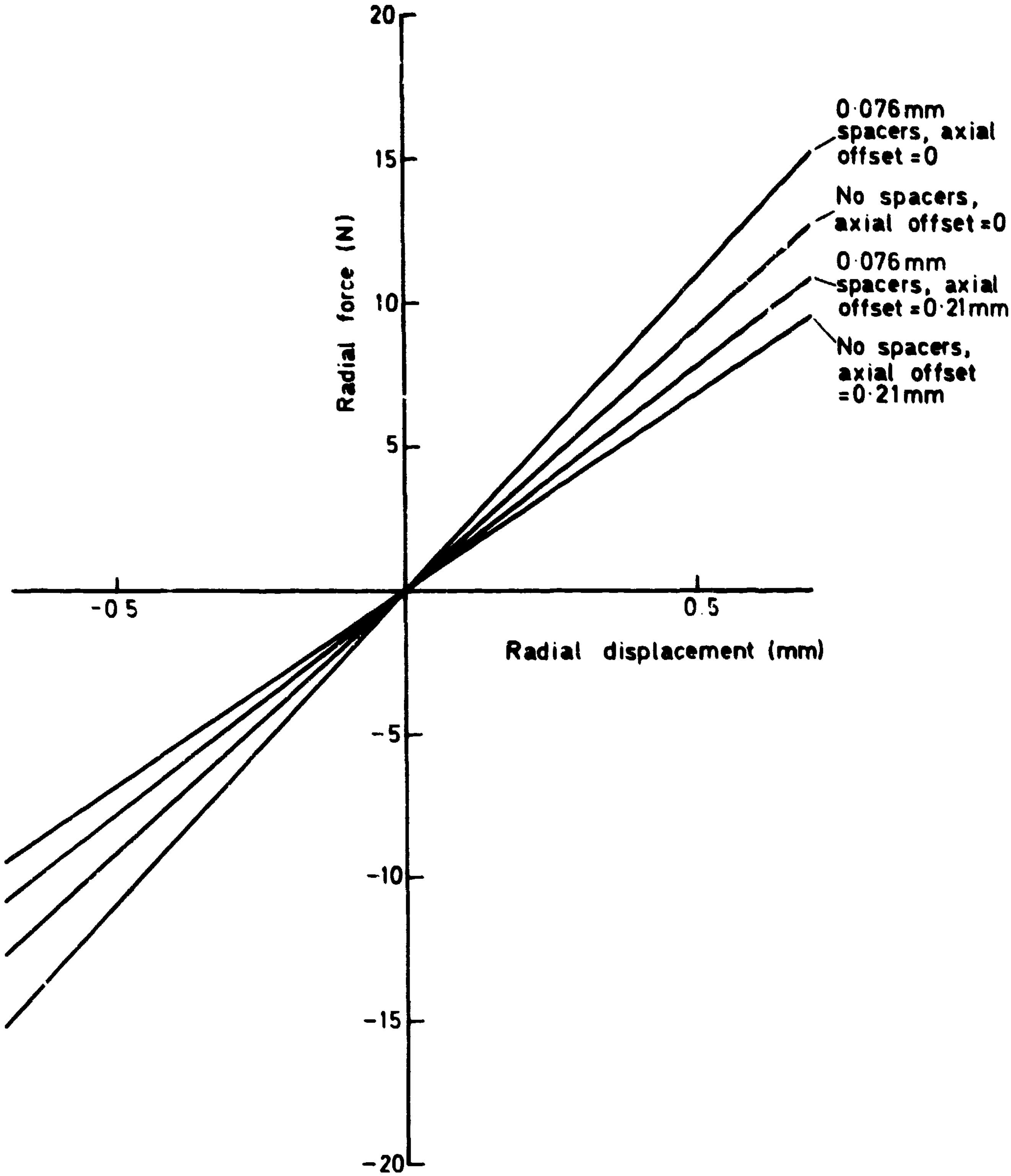

Fig.6 Variation of radial force with displacement using 1·5mm HERA rings with and without spacers to compare the effect of an axial offset

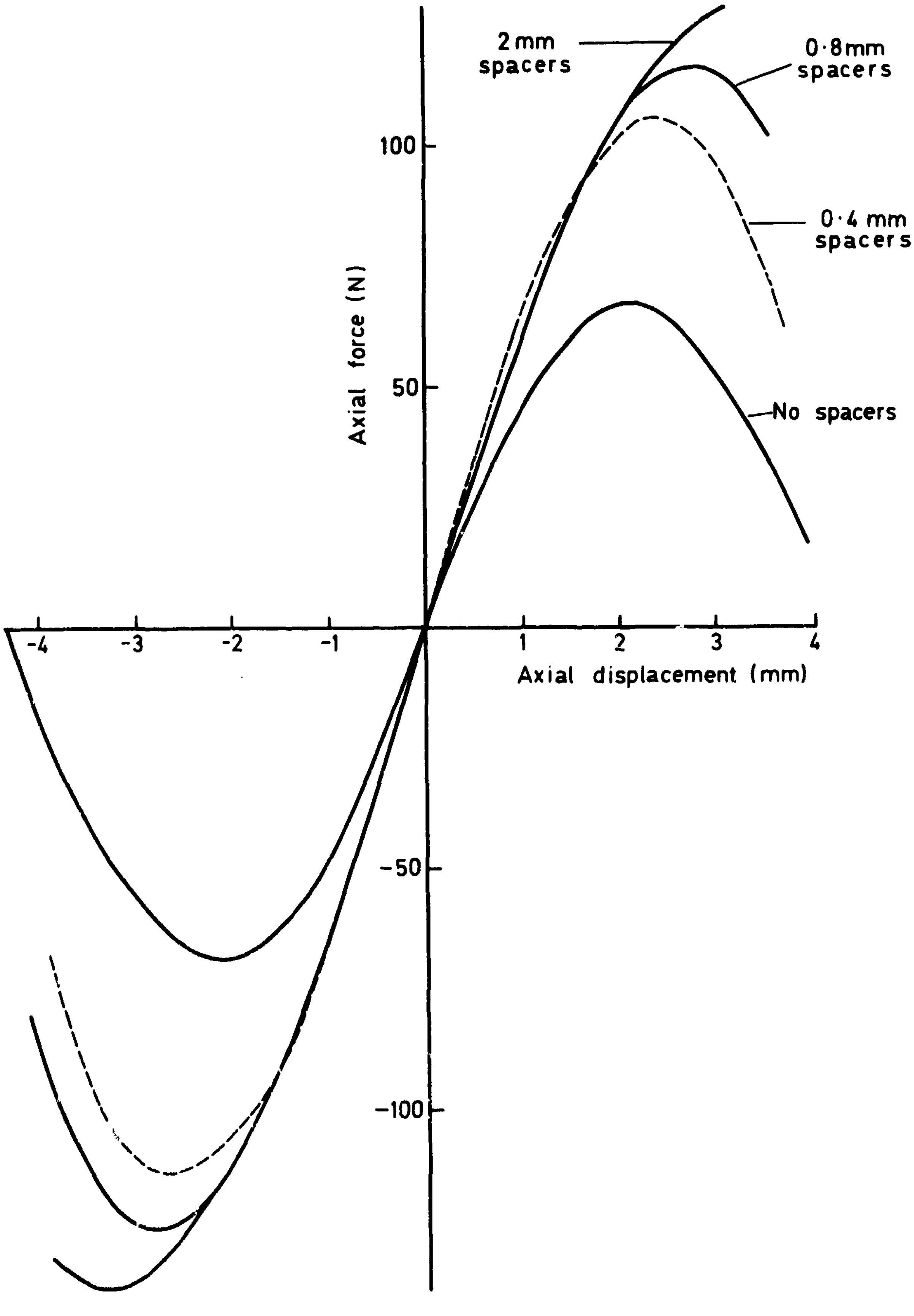

Fig.7 Variation of axial force with displacement using 4mm HERA rings and thick iron spacers

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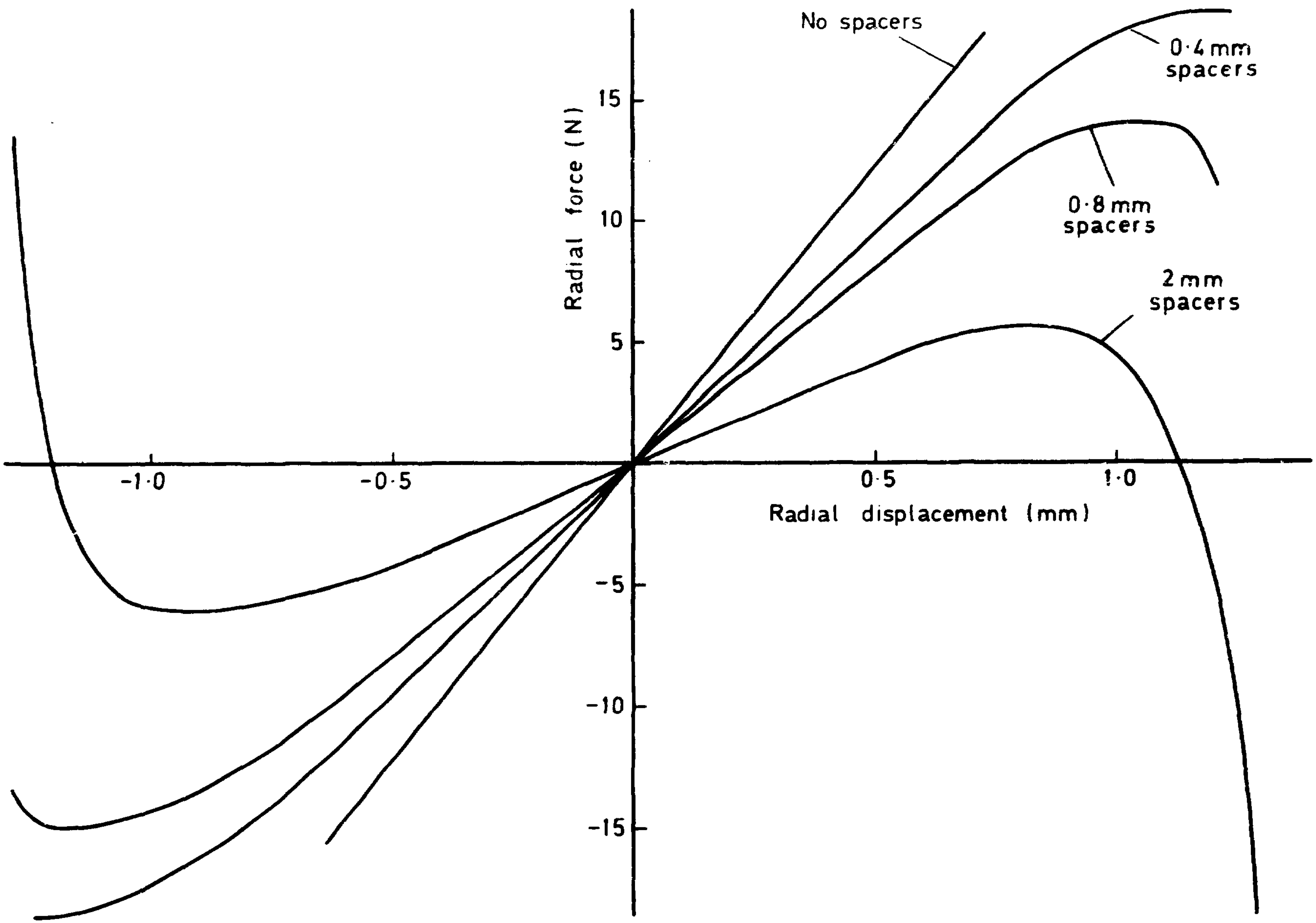

Fig.8 Variation of radial force with displacement using 4 mm HERA rings and thick iron spacers

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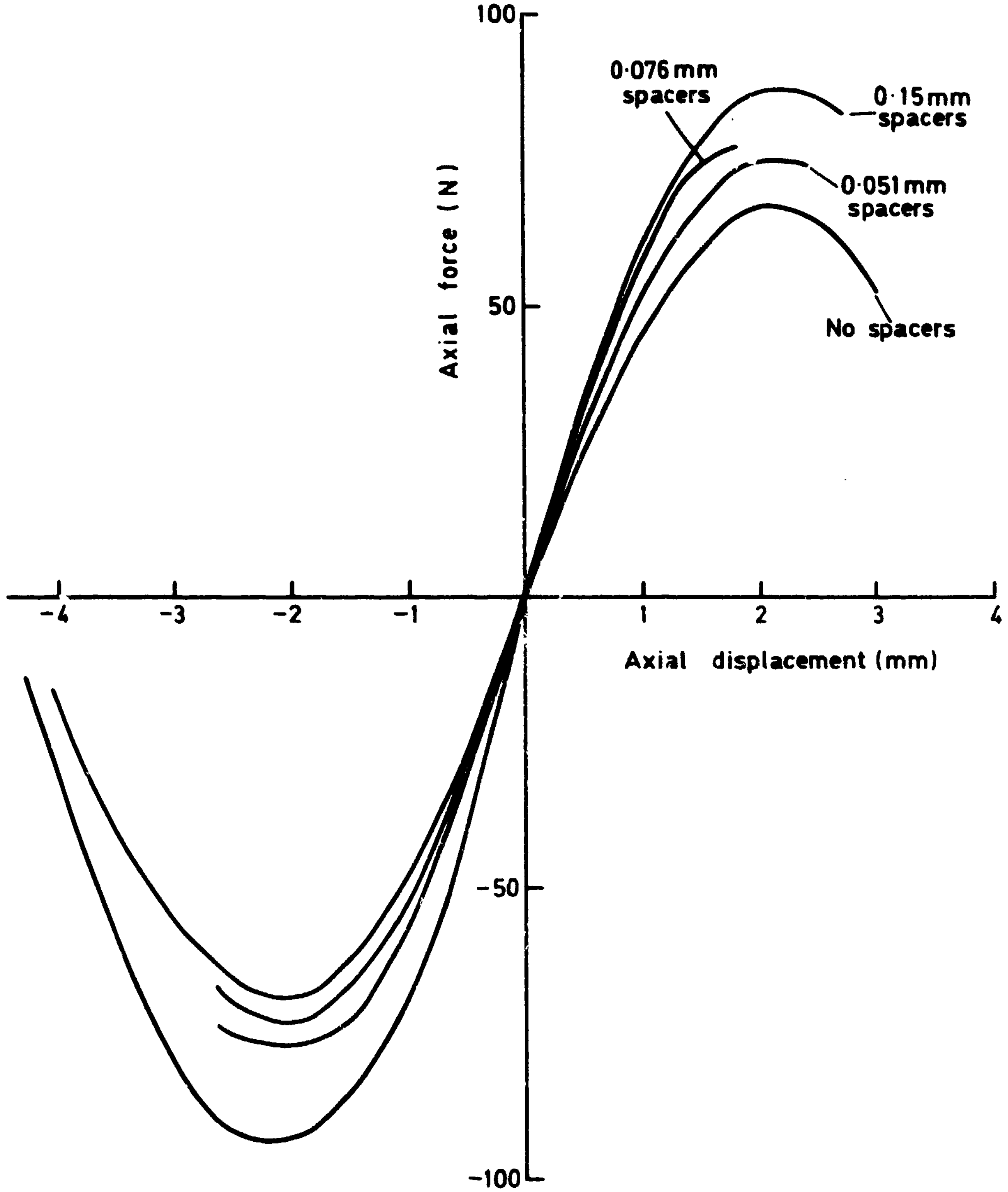

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Fig. 9 Variation of axial force with displacement using 4mm HERA rings and thin iron spacers

Fig.10

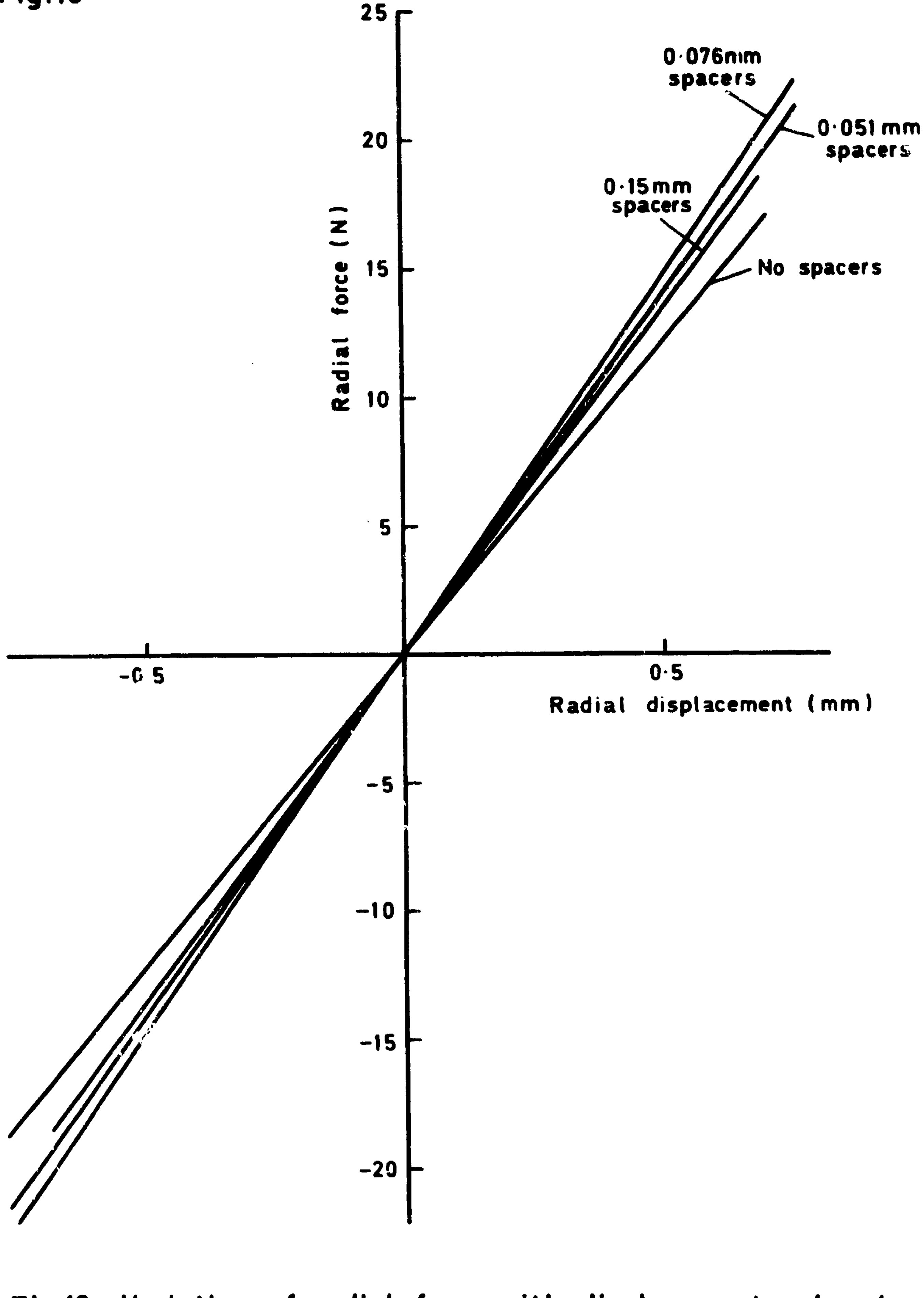

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Fig.10 Variation of radial force with displacement using 4mm HERA rings and thin iron spacers

Fig.11

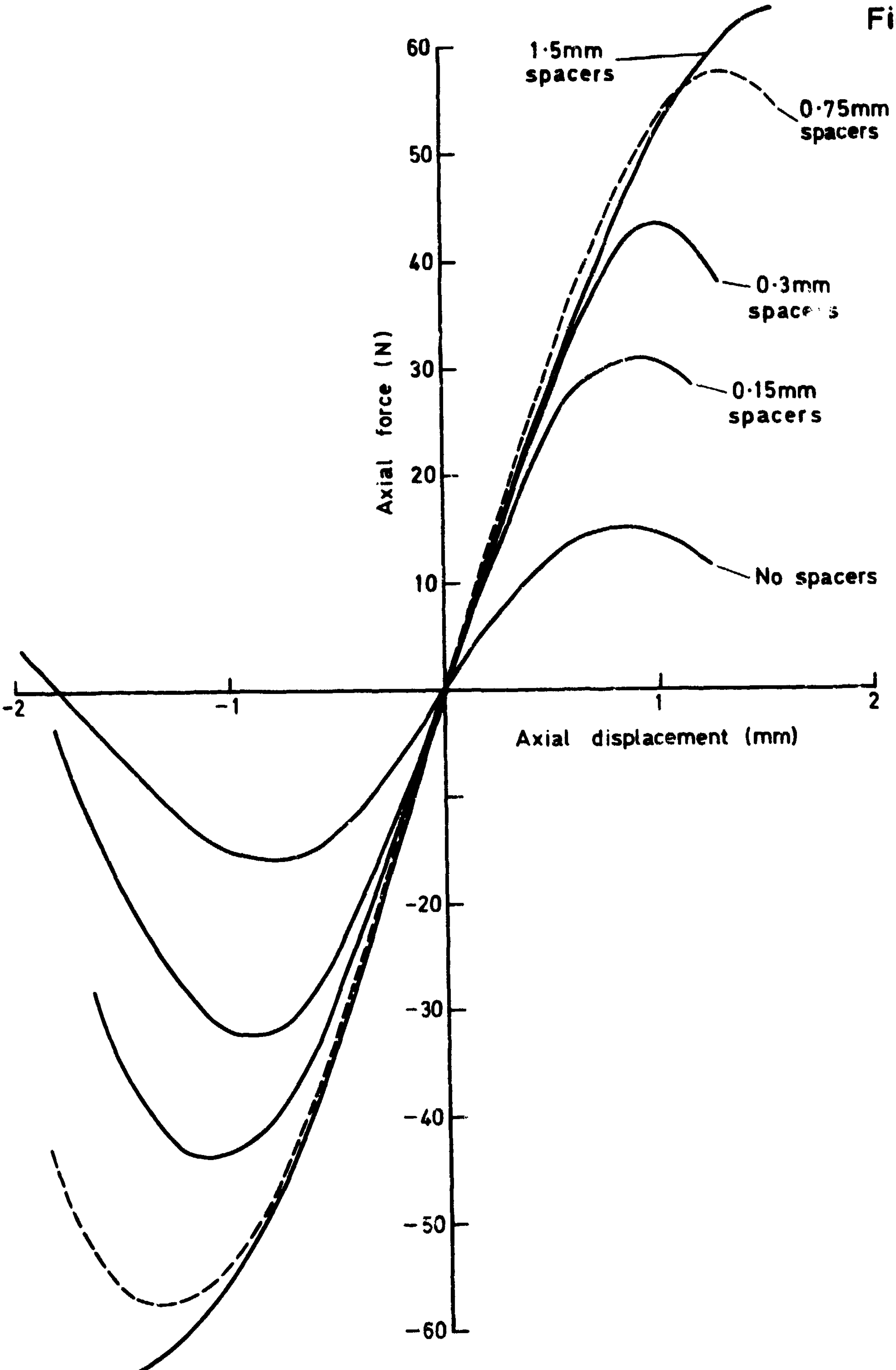

Fig.11 Variation of axial force with displacement using 1·5mm HERA rings and thick iron spacers

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Fig. 12

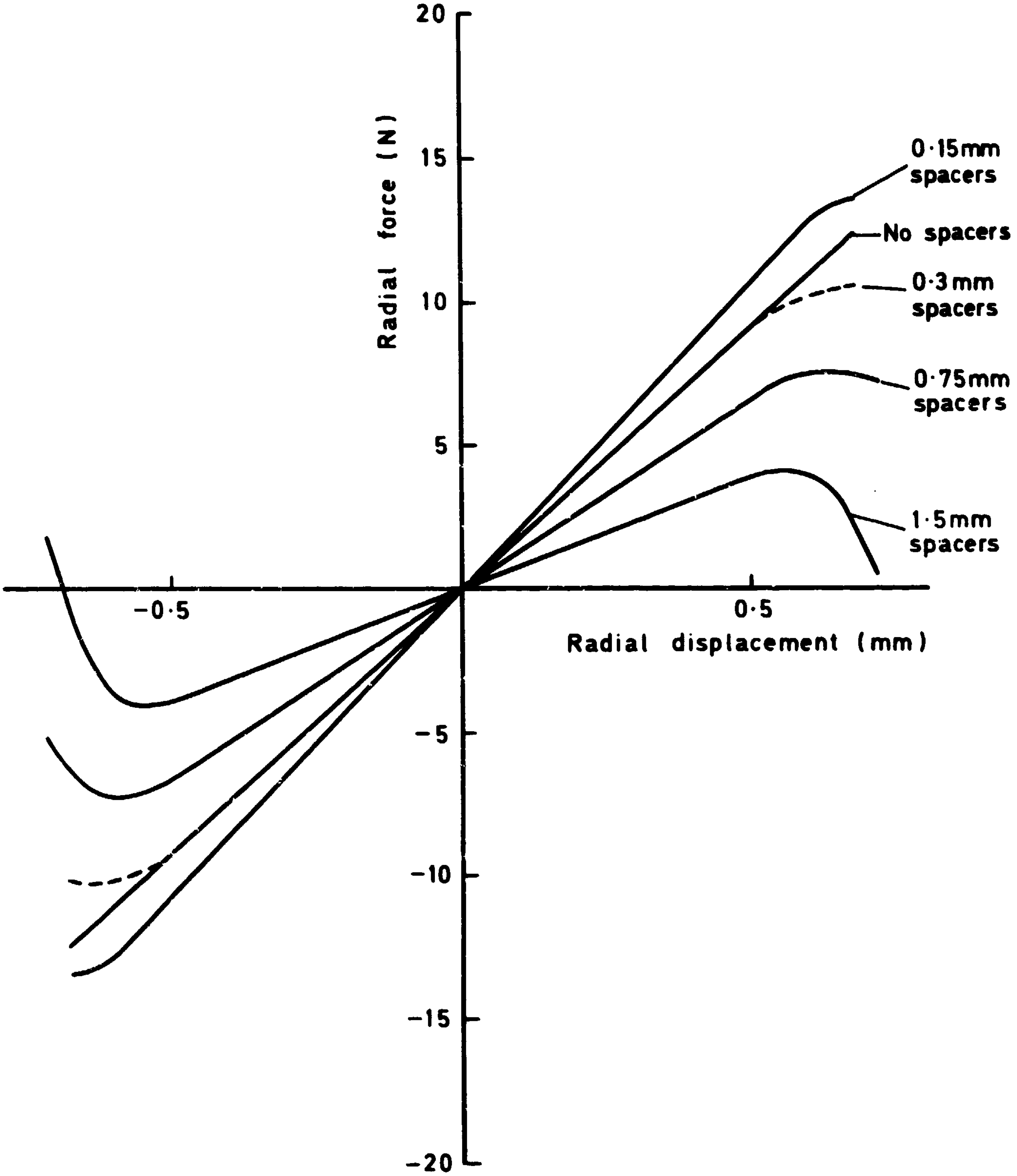

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Fig. 12 Variation of radial force with displacement using 1·5mm HERA rings and thick iron spacers

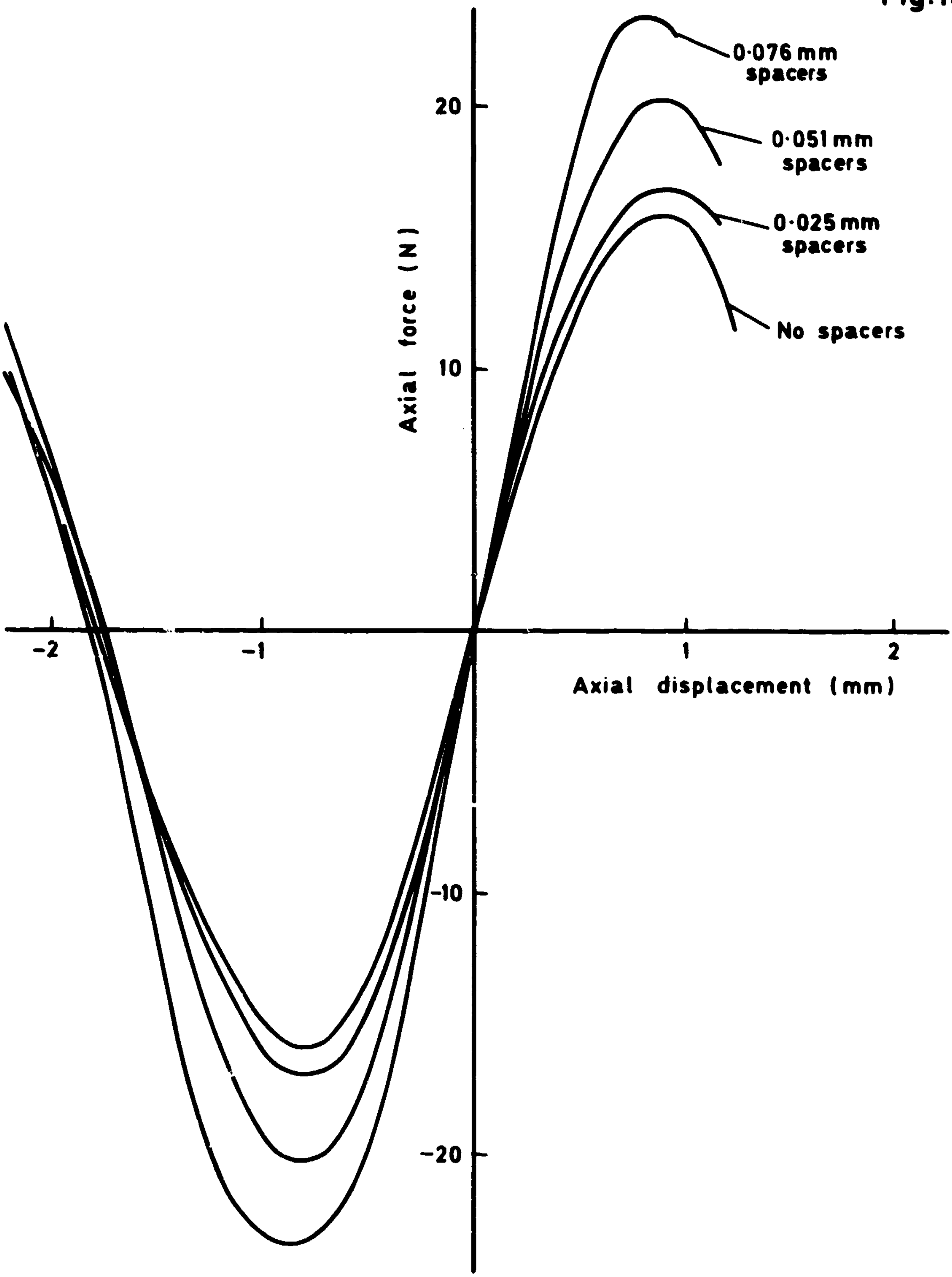

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Fig.13 Variation of axial force with displacement using 1·5mm HERA rings and thin iron spacers

Fig.14

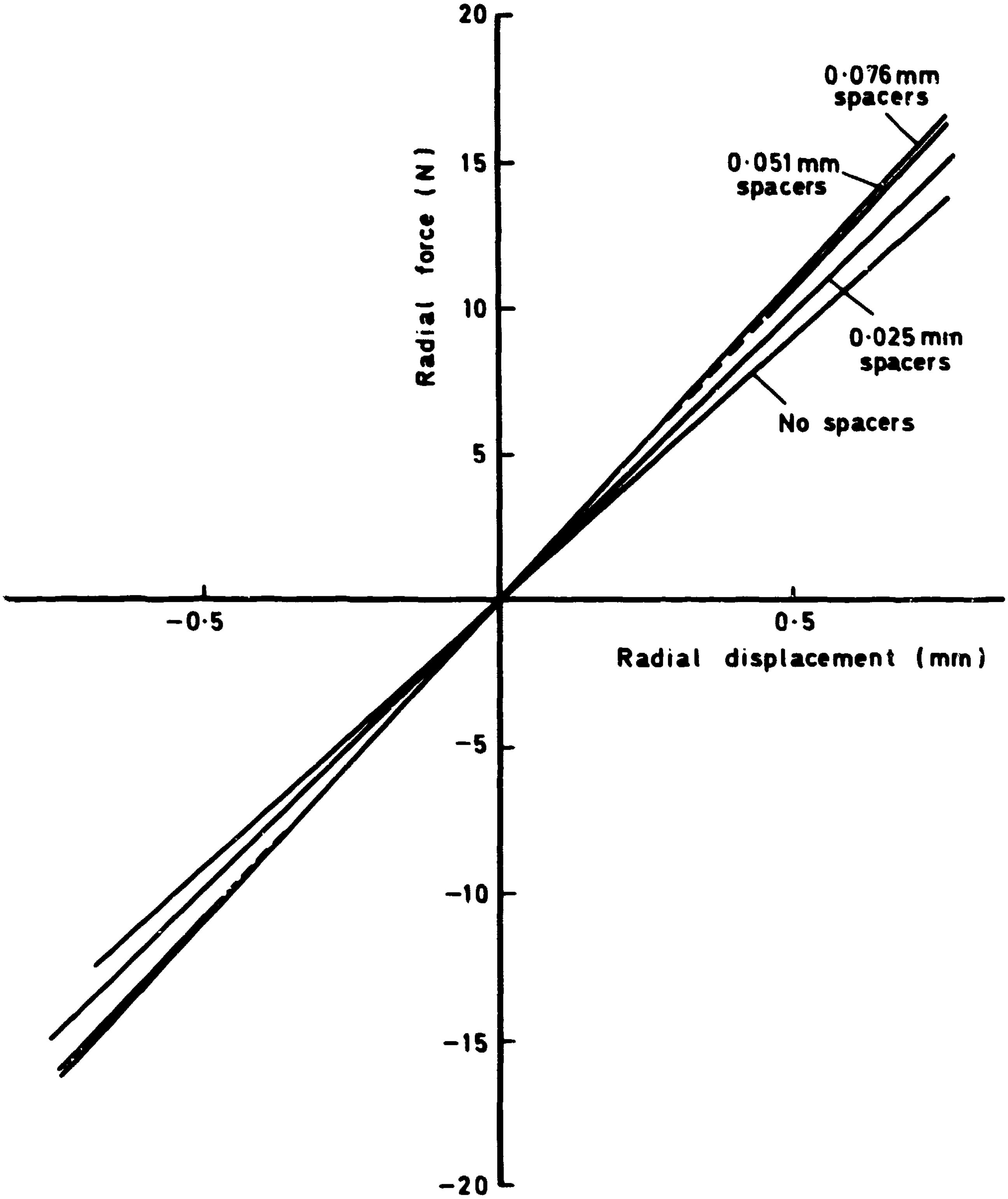

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Fig.14 Variation of radial force with displacement using 1·5mm HERA rings and thin iron spacers

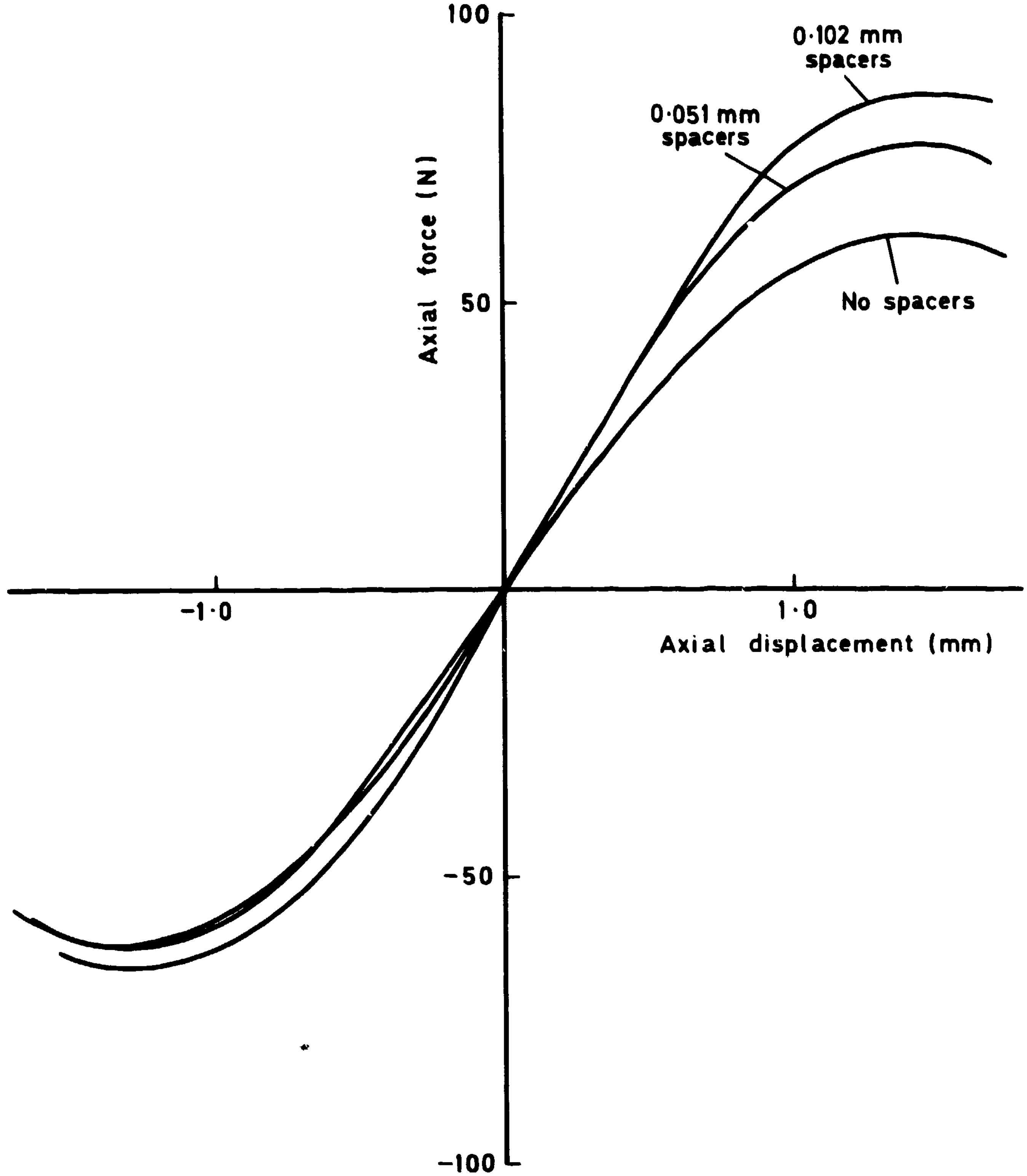

Fig. 15 Variation of axial force with displacement using samarium cobalt rings with thin iron spacers

Fig.16

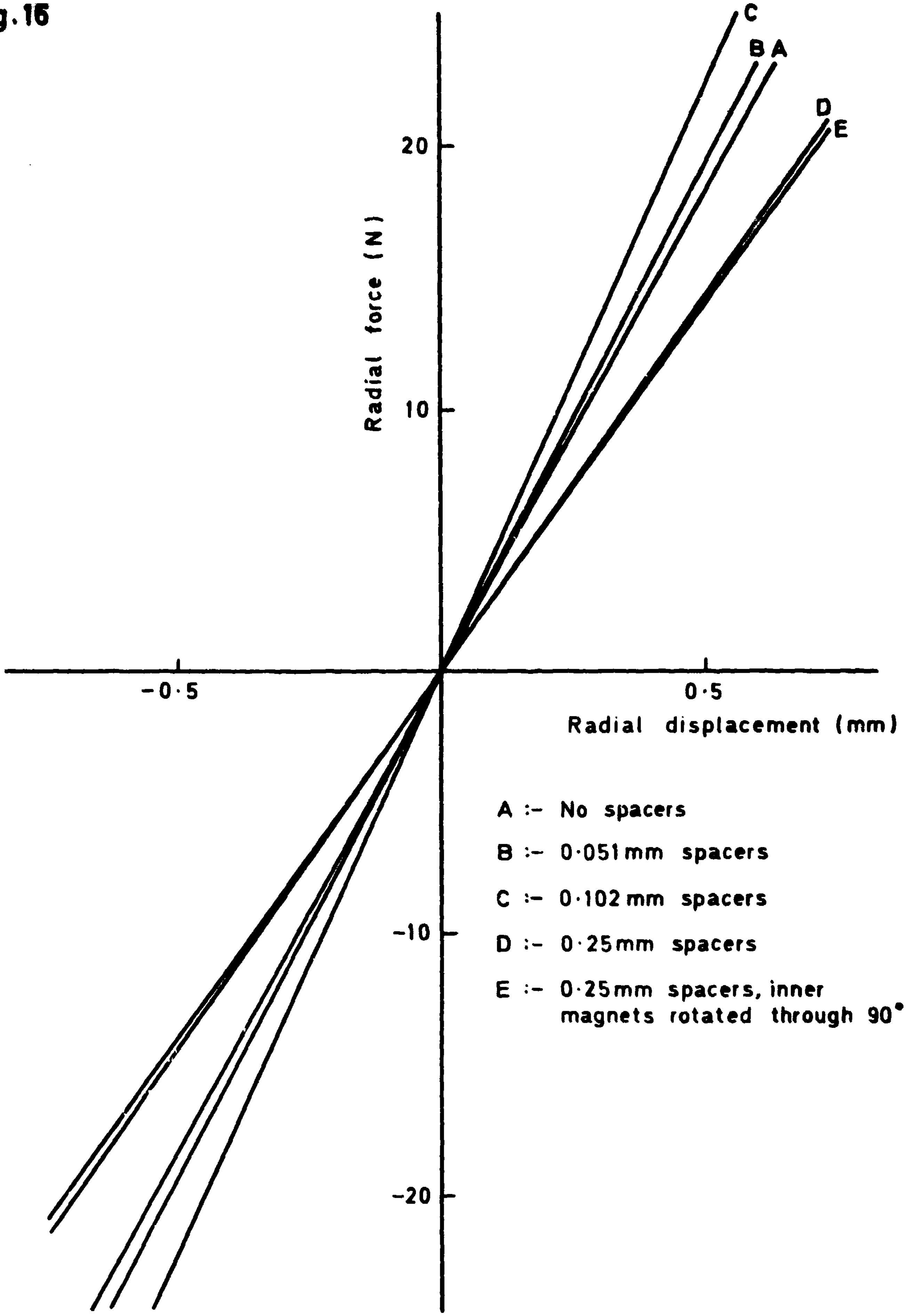

Fig.16 Variation of radial force with displacement using samarium cobalt rings and iron spacers

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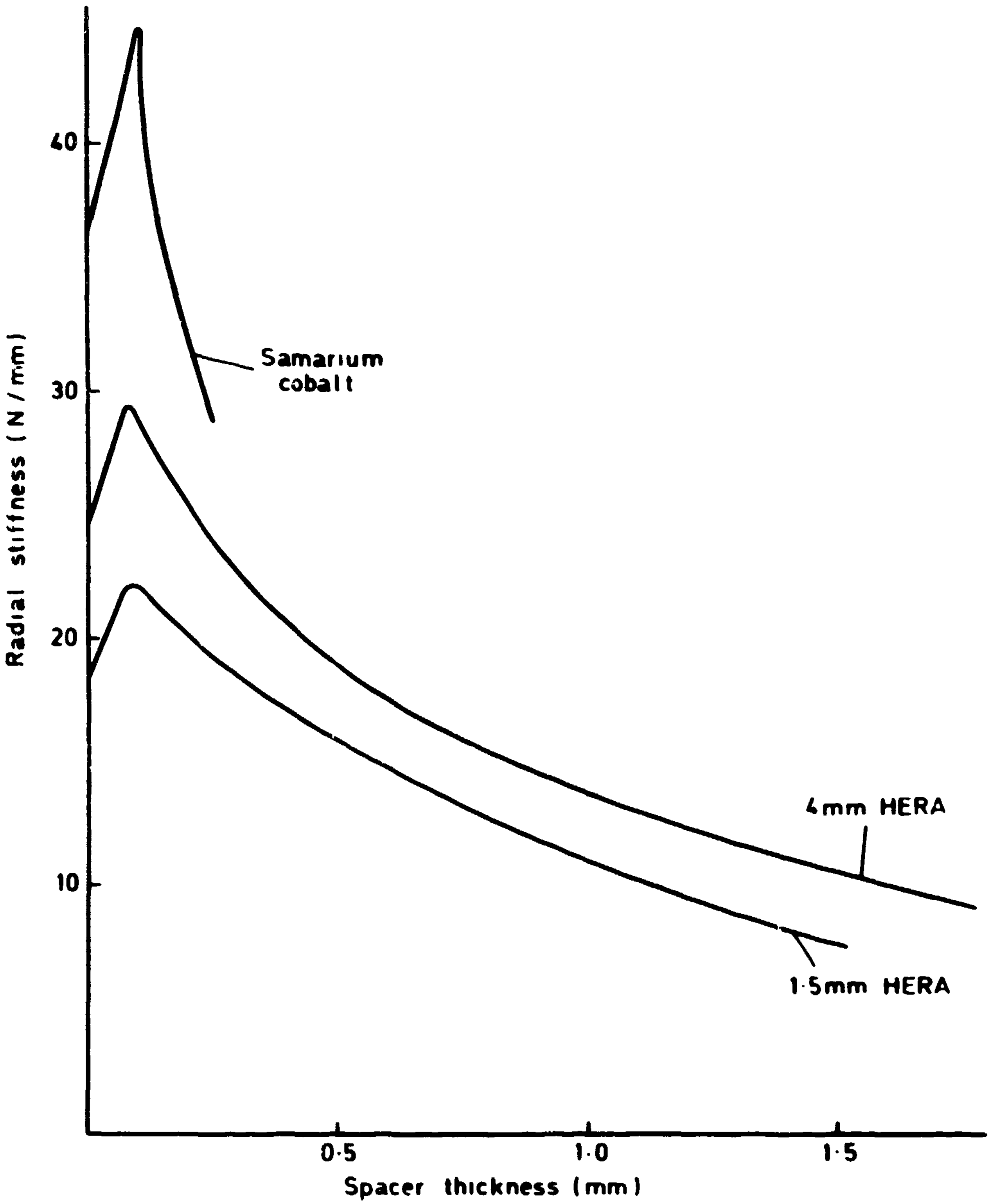

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Fig.17 Variation of radial stiffness with iron spacer thickness using thin HERA, thick HERA and samarium cobalt magnets

Fig. 18

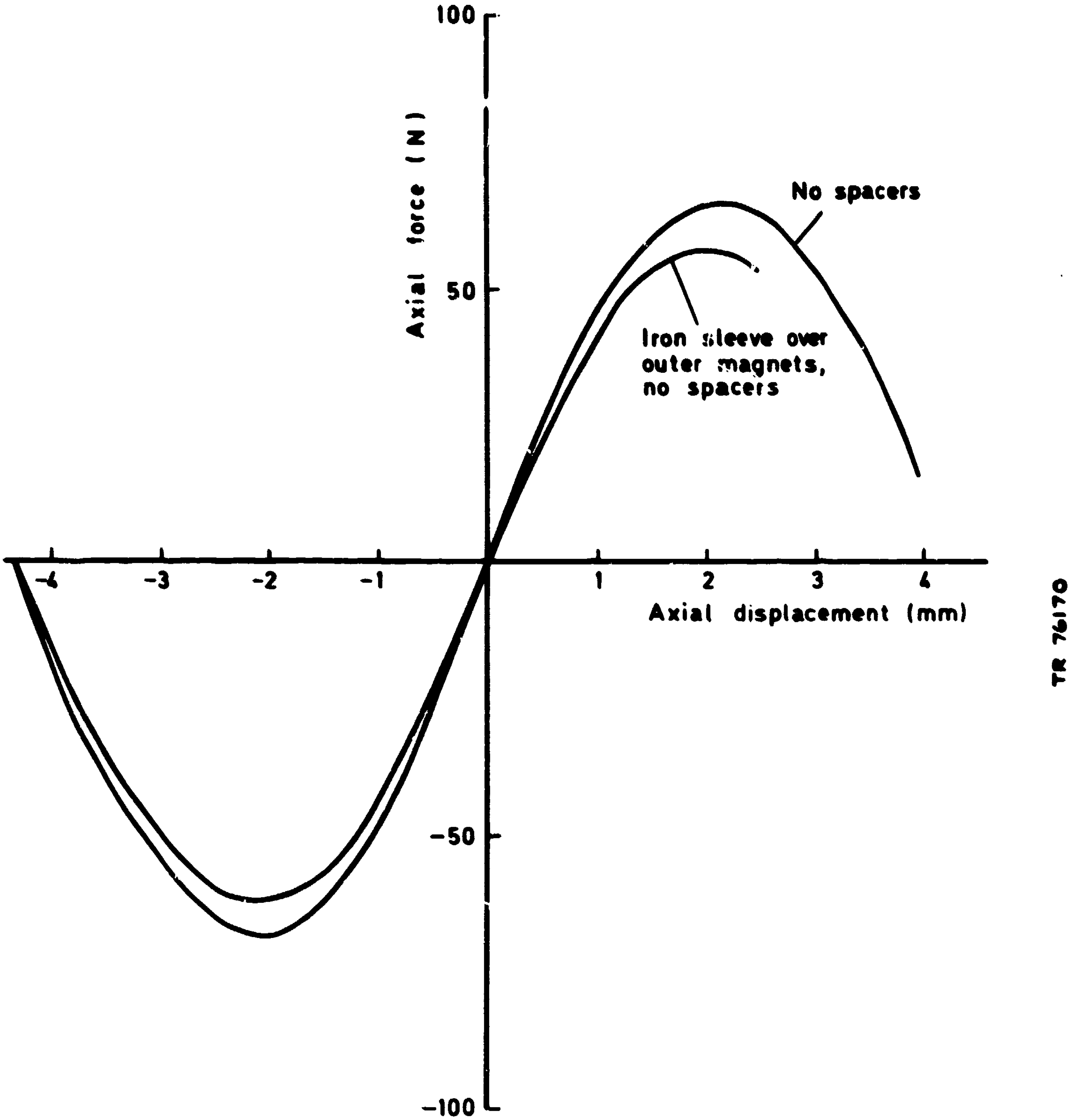

Fig. 18 Variation of axial force with displacement using 4 mm HERA rings and iron sleeving

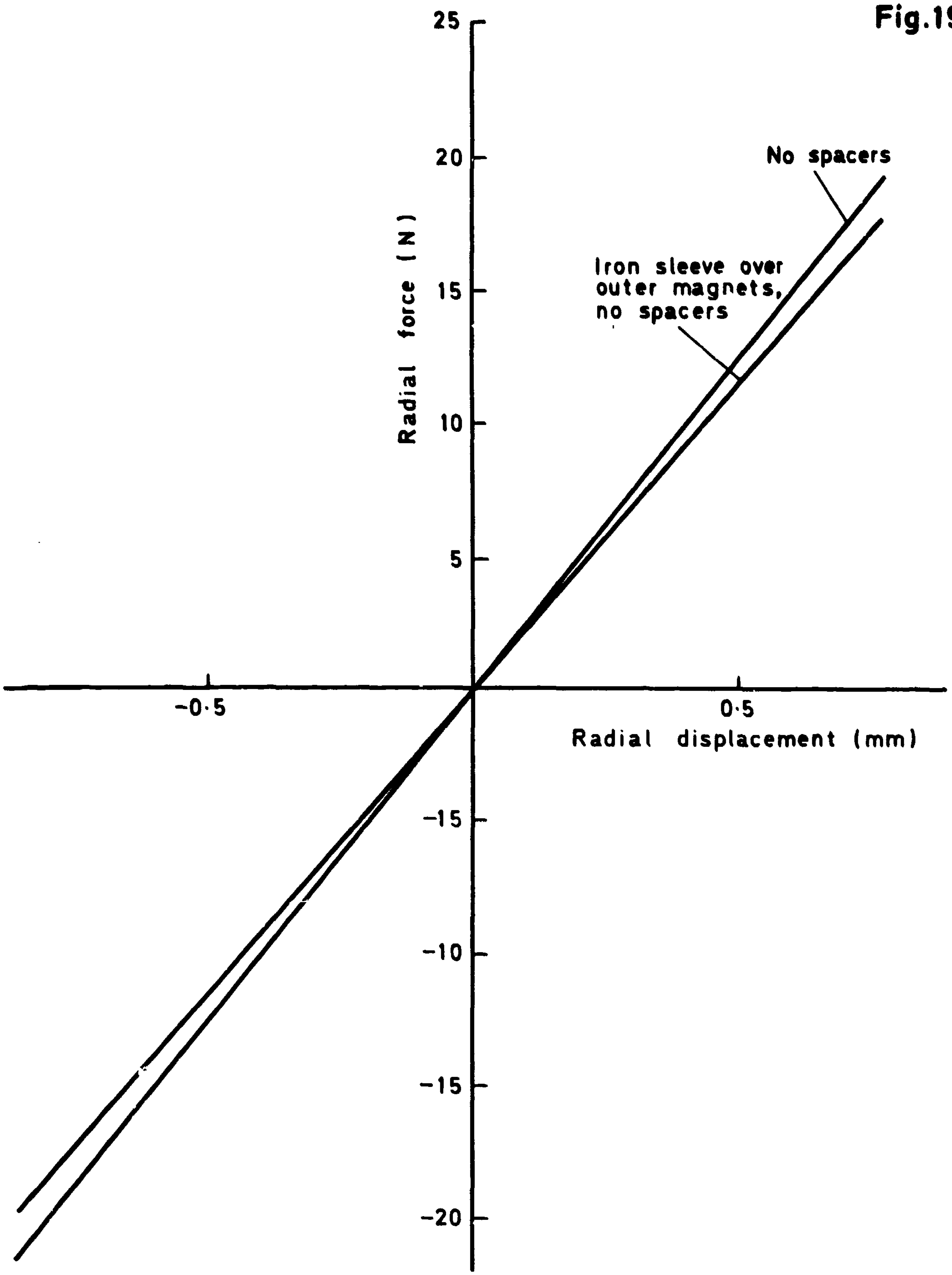

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Fig.19 Variation of radial force with displacement using 4mm HERA rings with iron sleeving

Fig. 20

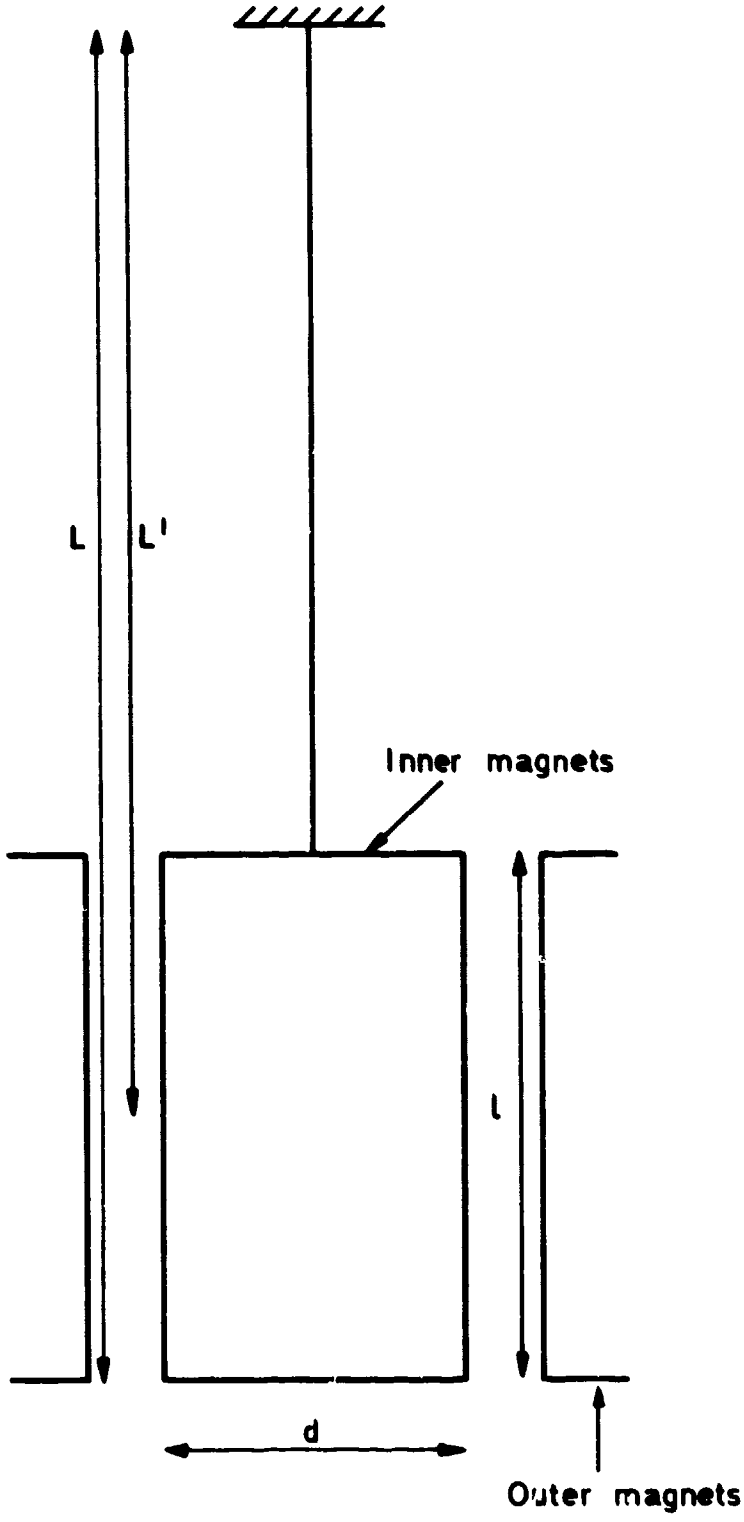

Fig. 20 Layout of simple pendulum used for verification of cross-axis stability criterion

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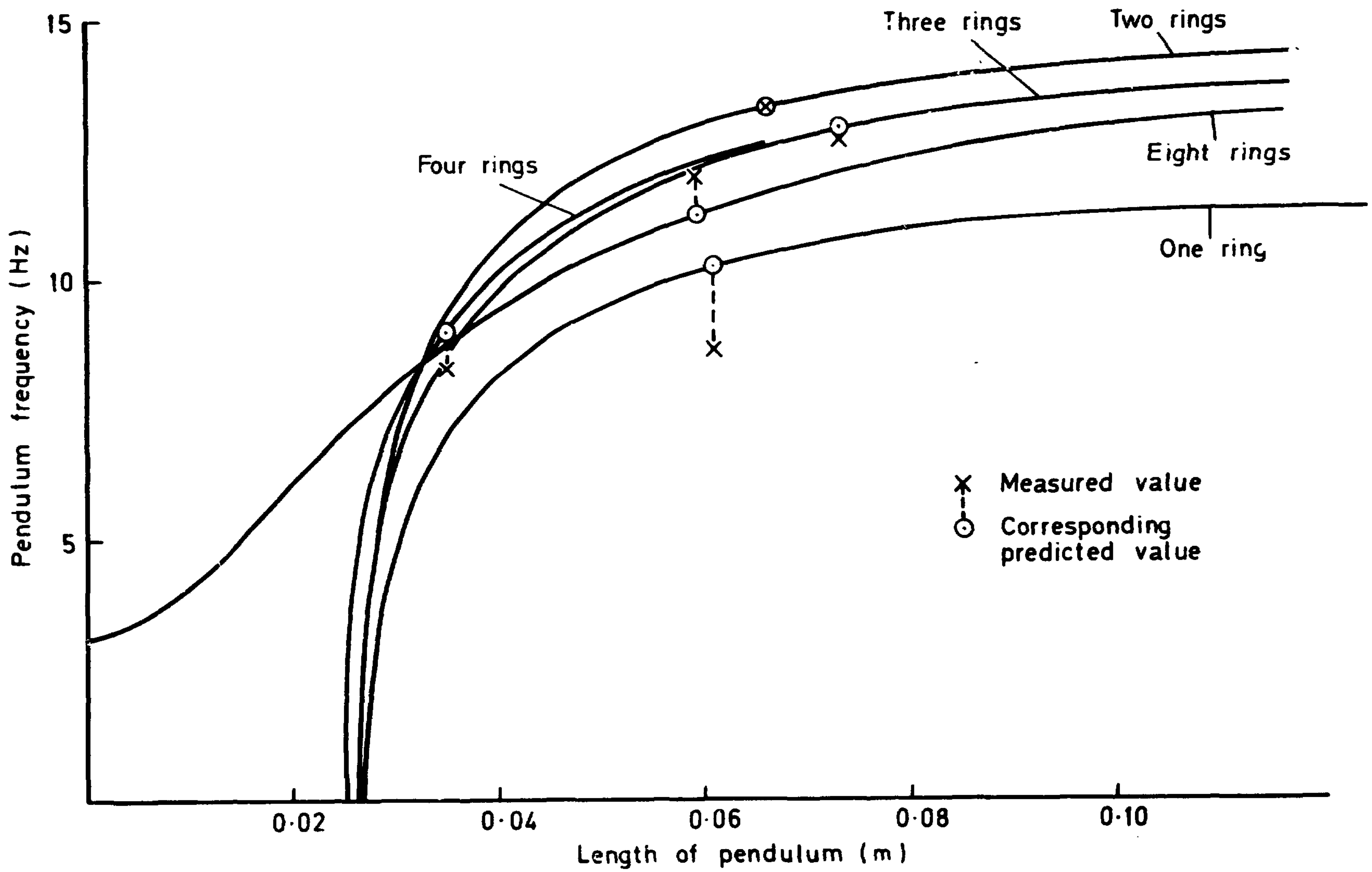

Fig. 21 Comparison between measured and predicted values of oscillation frequency of short pendulums made of various numbers of magnadur rings; theoretical variation of similar pendulums frequencies with length

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17. Abstract

Magnetic suspension systems can meet the requirements for spacecraft momentum wheel bearings. The main aim of the work described in this Report was to investigate the effects of interleaving soft iron spacer rings of various thicknesses between the magnetic rings of a repulsion type magnetic bearing. An optimum thickness of iron ring was found which produced a maximum increase in radial stiffness over the stiffness obtained without iron spacers. The magnetic inhomogeneity of the magnets was measured and found to have a small effect on the radial stiffness. Theory predicts that a single repulsion bearing will be cross-axially stable if the ratio of its length to diameter exceeds $\sqrt{3}$. This value was confirmed within the uncertainty of the experiment. The external magnetic fields from representative bearing assemblies were measured.

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